"Any sufficiently advanced technology is indistinguishable from magic"

Arthur C. Clarke

New Tricks with an Old Tool: Neutron Spin Echo Applied to Reflectometry and SANS

By

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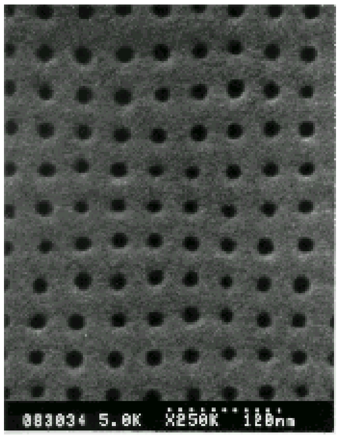
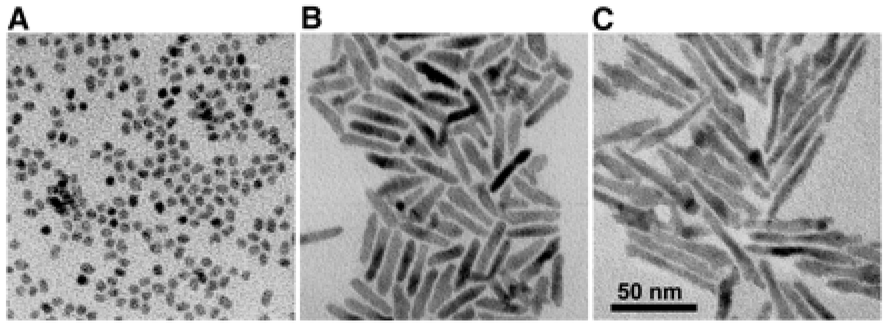
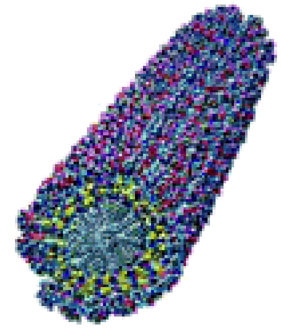
Nanoscience & Biology Need Structural Probes for 1-1000 nm



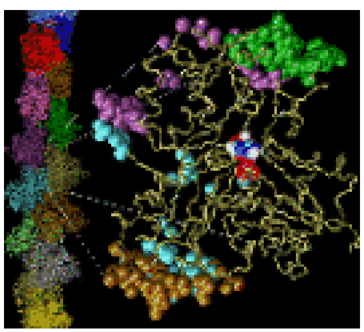
10 nm holes in PMMA



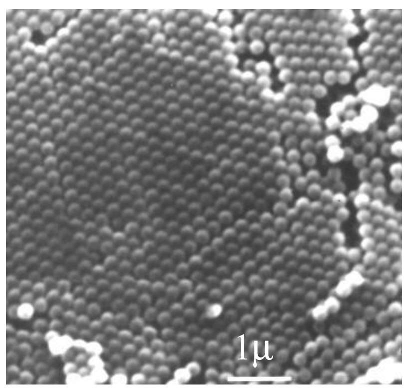
CdSe nanoparticles



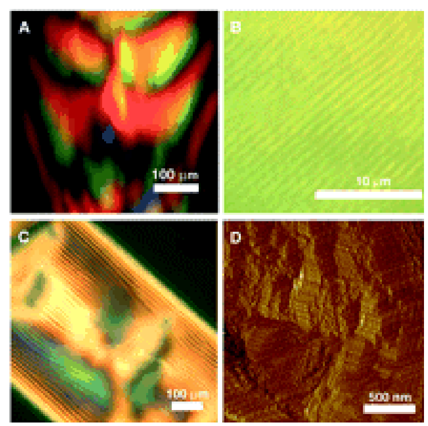
Peptide-amphiphile nanofiber



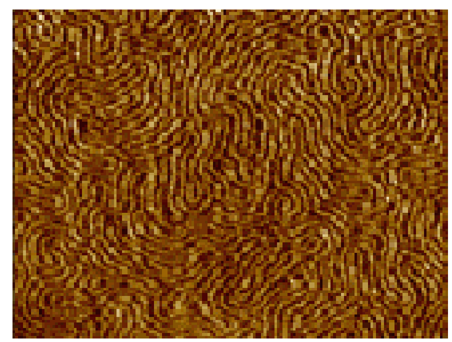
Actin



Si colloidal crystal



Structures over many length scales in self-assembly of ZnS and cloned viruses



Thin copolymer films

Current Limitations of Neutron Scattering for Nanoscience and Biology

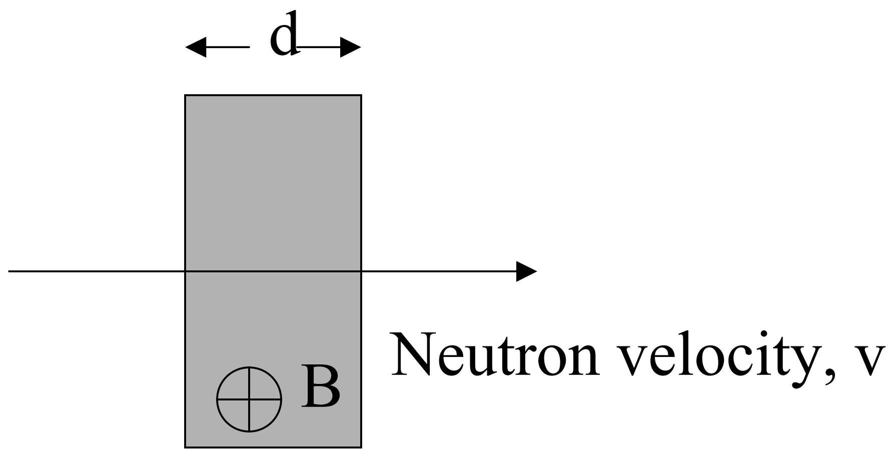
- Difficult to probe lengths much larger than a 100 nm with SANS
- Measurement of reflectivity is often limited by diffuse scattering or incoherent background
- No routine measurement of in-plane structures of thin films
- Time scales for kinetic measurements with SANS are quite long so that special systems have to be chosen for such measurements
- Very limited measurement of inelastic scattering from thin films

Tight collimation is incompatible with high signal intensity

Neutron Spin Echo (NSE) uses Larmor Precession to "Code" Neutron Velocities

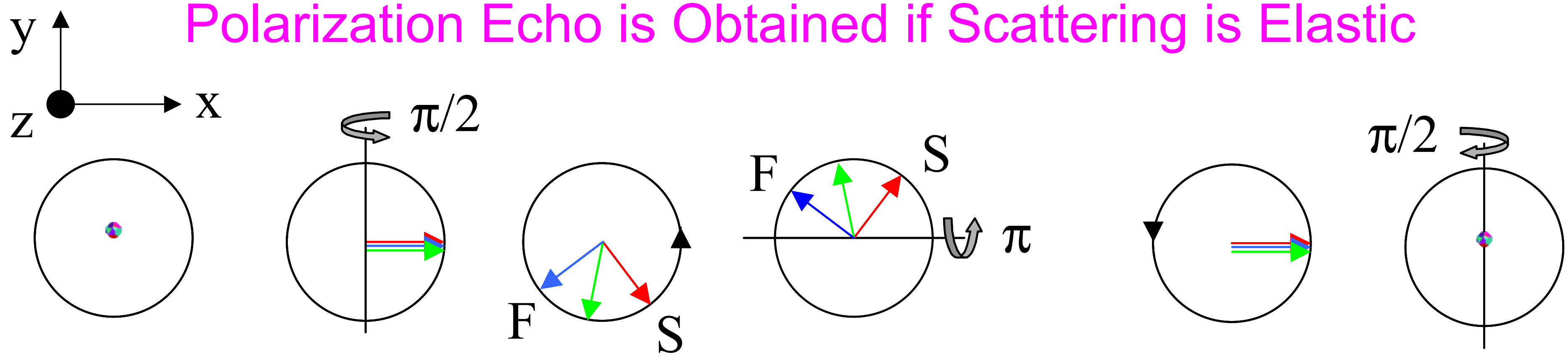
- A neutron spin precesses at the Larmor frequency in a magnetic field, B. $\omega_L = \gamma B$
- The total precession angle of the spin, ϕ, depends on the time the neutron spends in the field

$$\phi = \omega_L t = \gamma B d / \mathrm{v}$$



$$\text{Number of turns} = \frac{1}{135.65}.B[Gauss].d[cm].\lambda[Angstroms]$$

In NSE, Neutron Spins Precess Before and After Scattering & a Polarization Echo is Obtained if Scattering is Elastic



Initially, neutrons are polarized along z

Rotate spins into x-y precession plane

Allow spins to precess around z: slower neutrons precess further over a fixed path length

Rotate spins through π about x axis

Elastic Scattering Event

Allow spins to precess around z: precession angle of all neutrons is the same at echo point if $\Delta E = 0$

Rotate spins to z and measure polarization

$$\boxed{\textit{Final Polarization},\ P = \langle \cos(\phi_1 - \phi_2) \rangle}$$

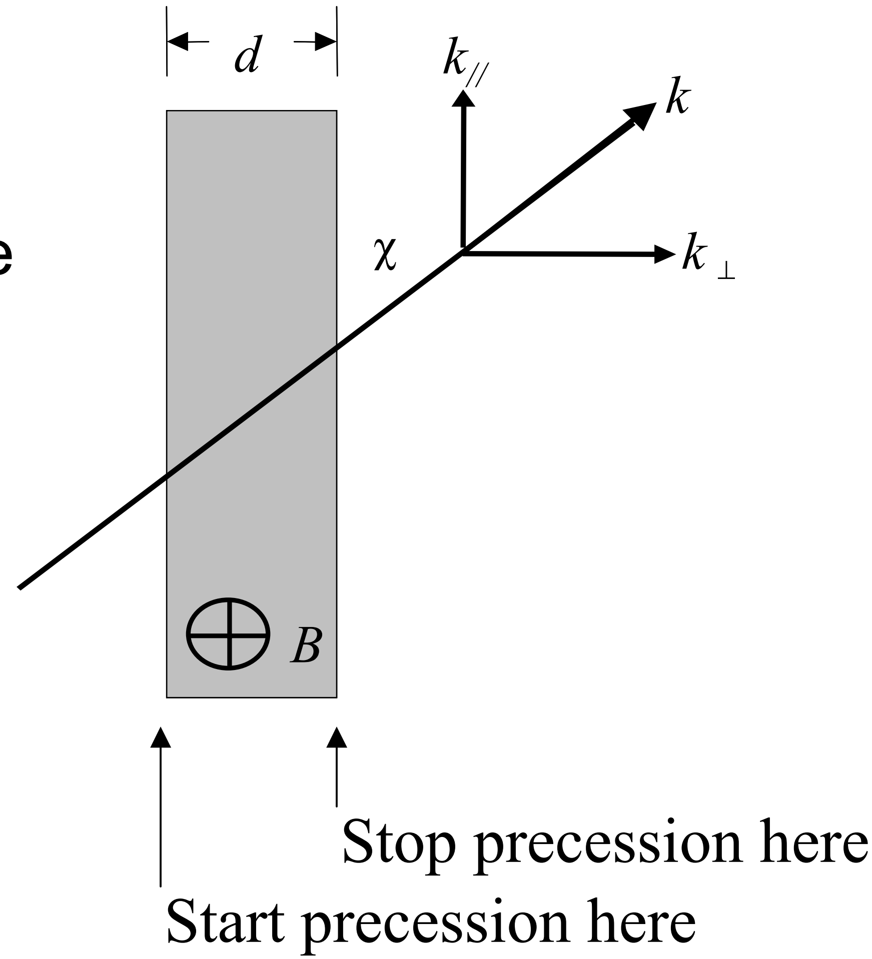
By "Inclining" the Magnetic-Field Region, Spin Precession Can Be Used to Code a Specific Component of the Neutron Wavevector

If a neutron passes through a rectangular field region at an angle, its total precession phase will depend only on $k_{\perp}$.

$$\omega_L = \gamma B$$

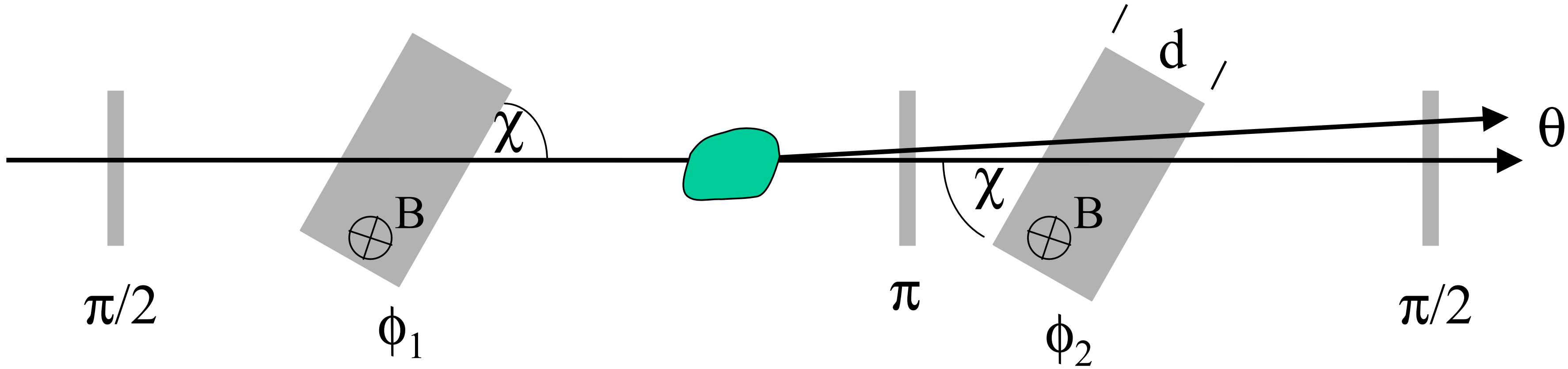
$$\phi = \omega_L t = \gamma B \frac{d}{\mathrm{v} \sin \chi} = \frac{KBd}{k_{\perp}}$$

with K = 0.291 (Gauss.cm.Å)$^{-1}$



With Bd = 1000 Gauss.cm & k = 1.5 Å^{-1} we get 1 radian change in ϕ for $\delta\chi \sim 0.2°$ at $\chi = 45°$ or for $\delta\chi \sim 0.01°$ at $\chi = 10°$

A Simple Example of Tilted Fields: SANS



- Any unscattered neutron (θ=0) experiences the same precession angles (ϕ_1 and ϕ_2) before and after scattering, *whatever its angle of incidence*
- Precession angles are different for scattered neutrons

$$\phi_1 = \frac{KBd}{k\sin\chi} \text{ and } \phi_2 = \frac{KBd}{k\sin(\chi+\theta)} \Rightarrow \cos(\phi_1 - \phi_2) \approx \cos\left[\frac{KBd\cos\chi}{k\ \ \sin^2\chi}\theta\right]$$

$$P = \int dQ.S(Q).\cos\left[\frac{KBd\cos\chi}{k^2\sin^2\chi}Q\right]$$

Polarization proportional to Fourier Transform of *S(Q)*

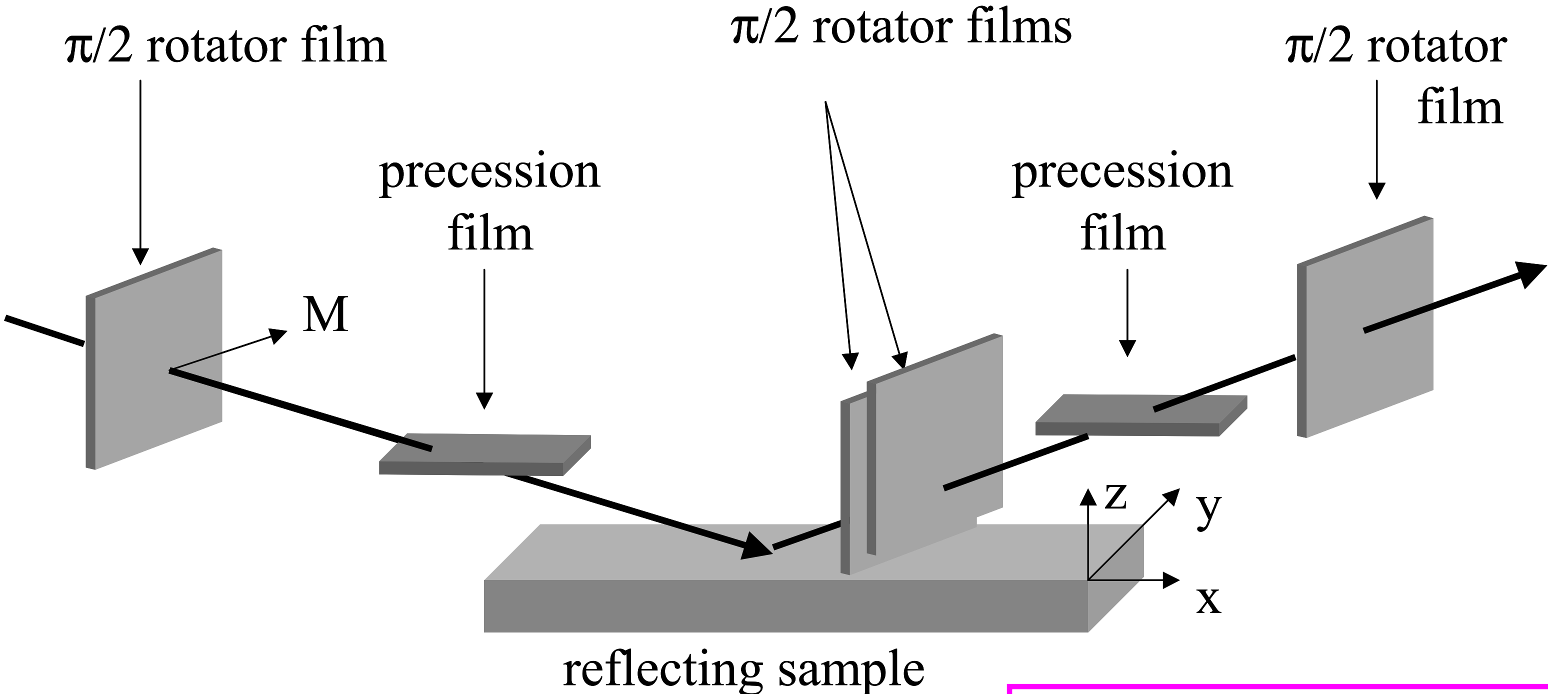
Spin Echo Length, $r = KBd\cos\chi/(k\sin\chi)^2$

How Large is the Spin Echo Length for SANS?

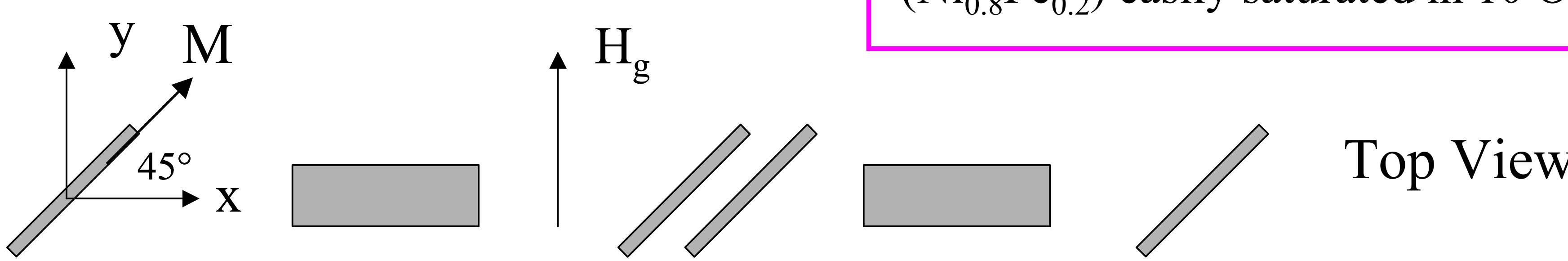
$Bd/\sin\chi$ (Gauss.cm)	λ (Angstroms)	χ (degrees)	r (Angstroms)
3,000	4	20	1,000
5,000	4	20	1,500
5,000	6	20	3,500
5,000	6	10	7,500

- It is relatively straightforward to probe length scales of ~ 1 micron
- Note amplification of r by decreasing χ and increasing λ

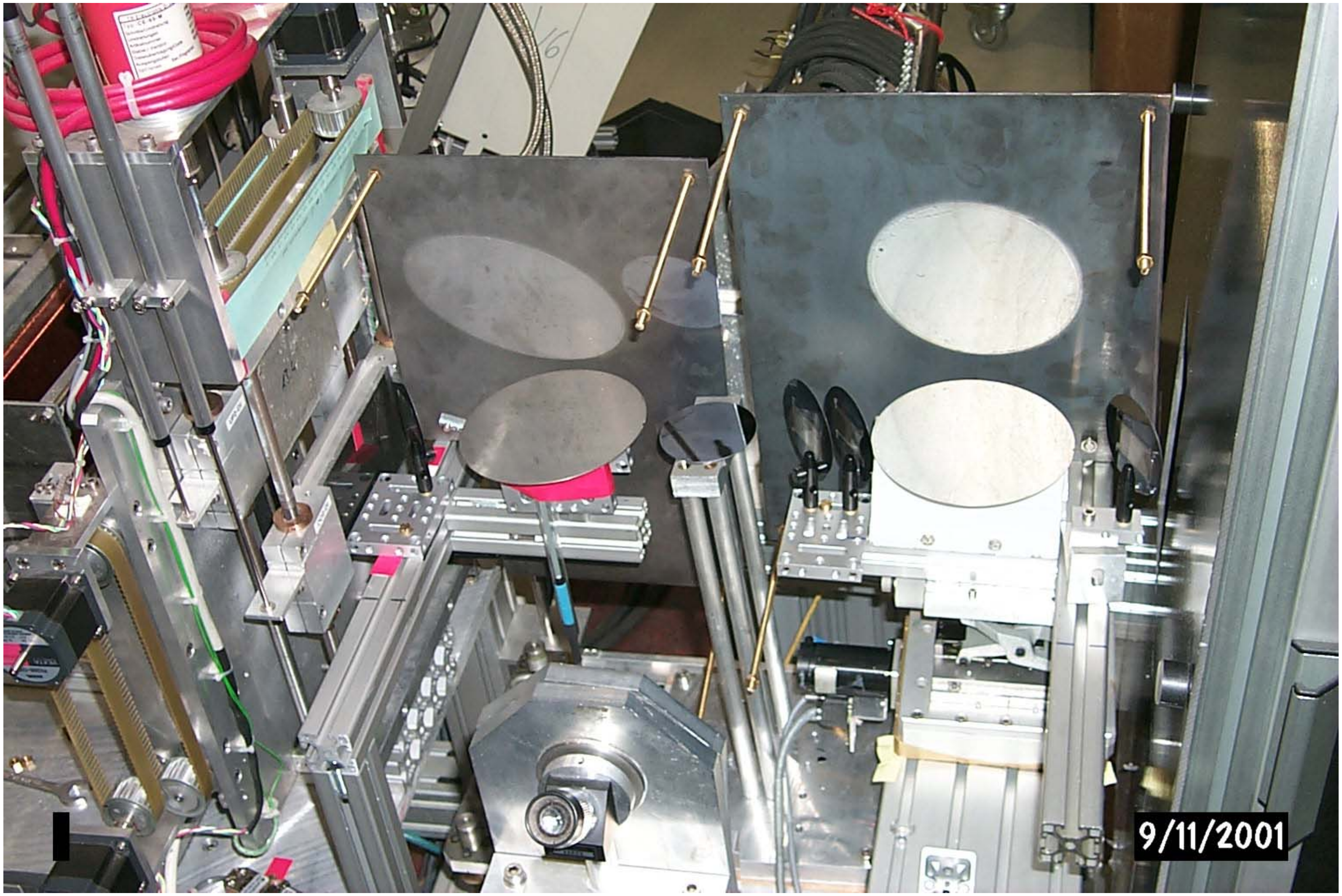
Discriminating Between Specular and Diffuse Neutron Reflection with Better than 0.5 mrad Angular Resolution



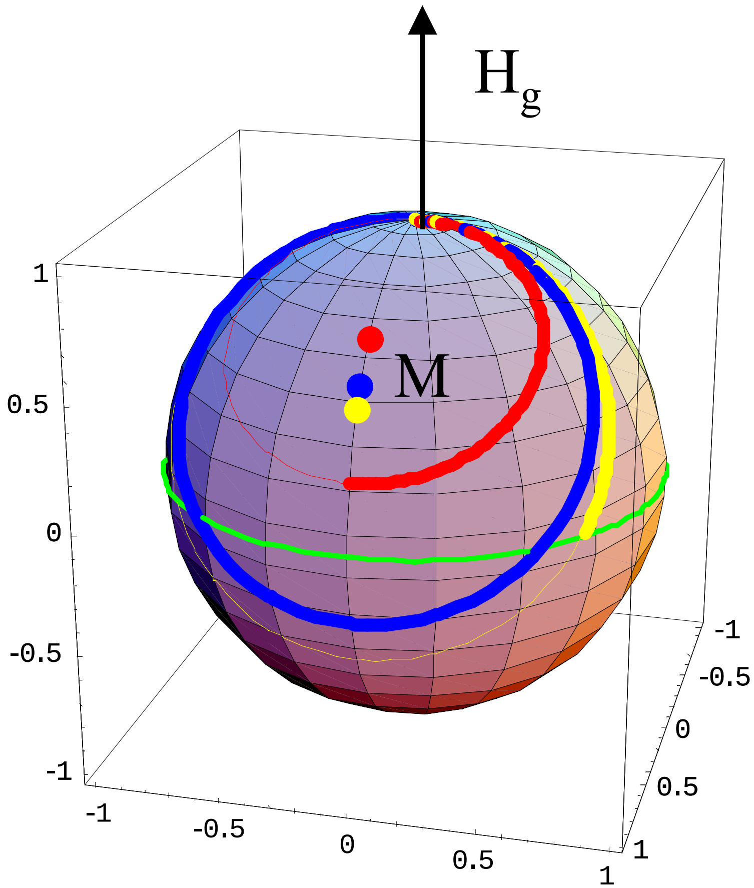
Rotator and precession films were ~30 μm thick Permalloy ($Ni_{0.8}Fe_{0.2}$) easily saturated in 10 Oe

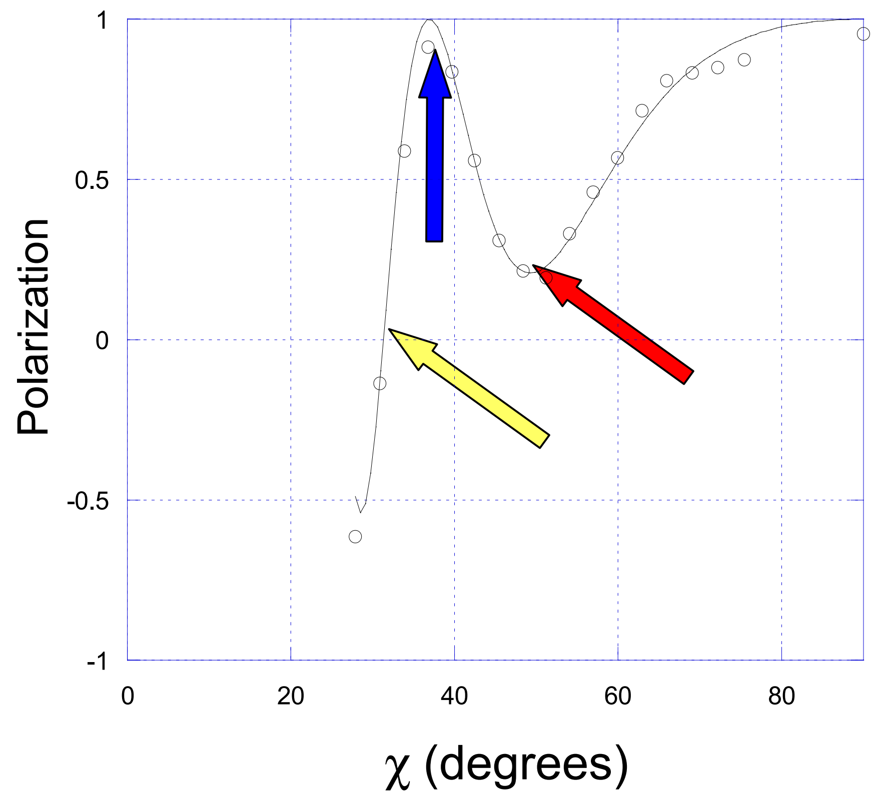


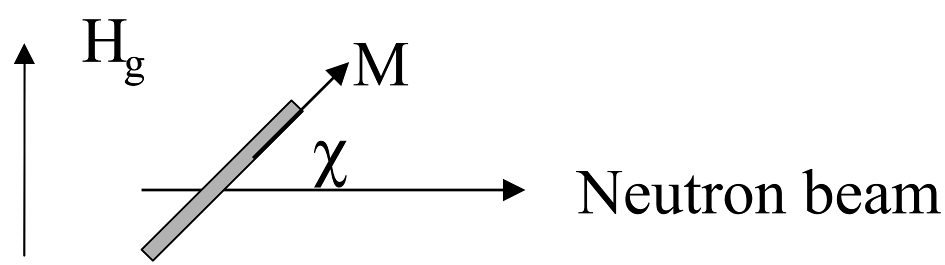
Experiment at Hahn-Meitner-Institut



A 30 μ Permalloy Film used as a Neutron Spin Rotator



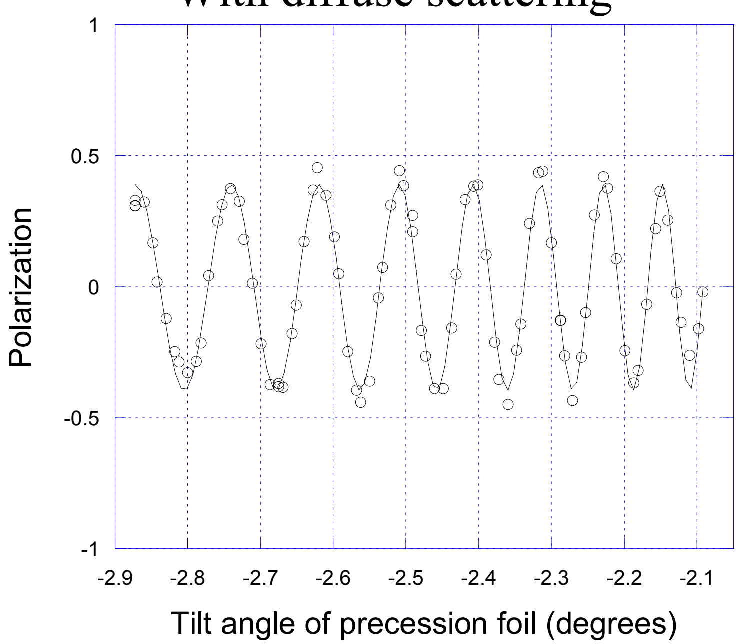




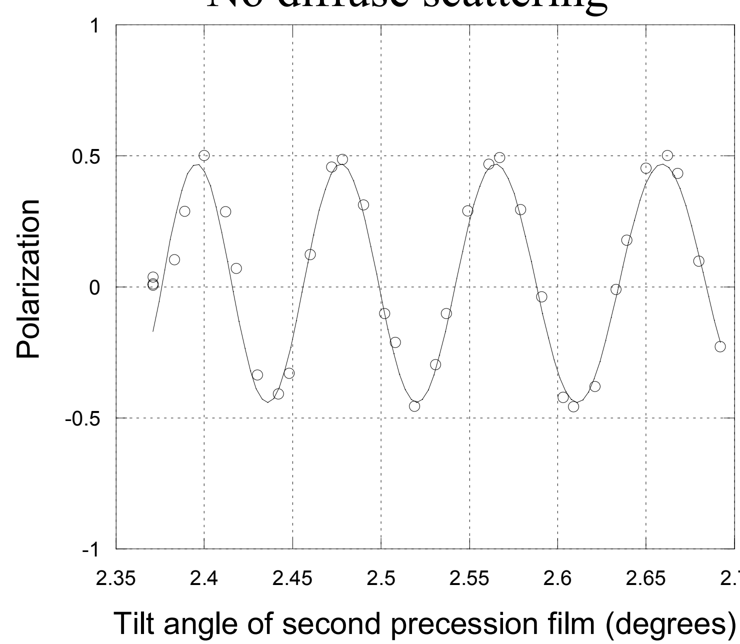
Experimental Results for Reflectometry

- 30 μm permalloy films magnetized by a guide field work well as π/2 rotators
- 30 μm permalloy films, magnetized by a guide field, work as "precession fields" but thickness variation limits echo amplitude to ~0.5
- Change in the echo amplitude was observed when beam was diffusely scattered
  - Our apparatus was sensitive to changes of about 0.02º in neutron trajectory

With diffuse scattering

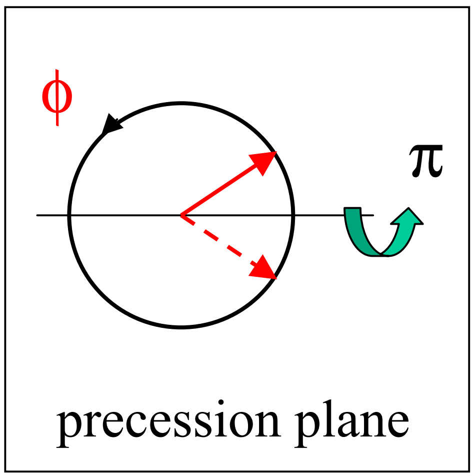


No diffuse scattering

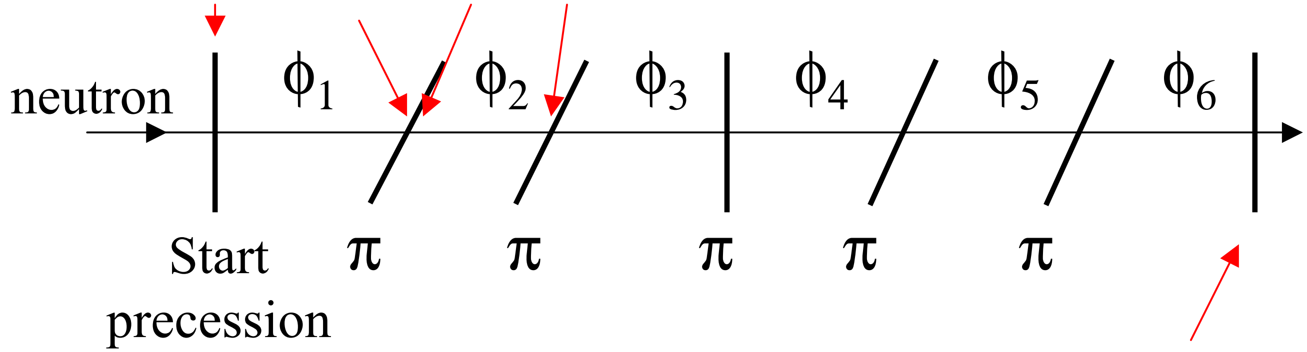


Using "Sign Reversal" to Implement Angle Coding

An element that performs a π rotation about an axis in the precession plane changes the sign of prior precession angles



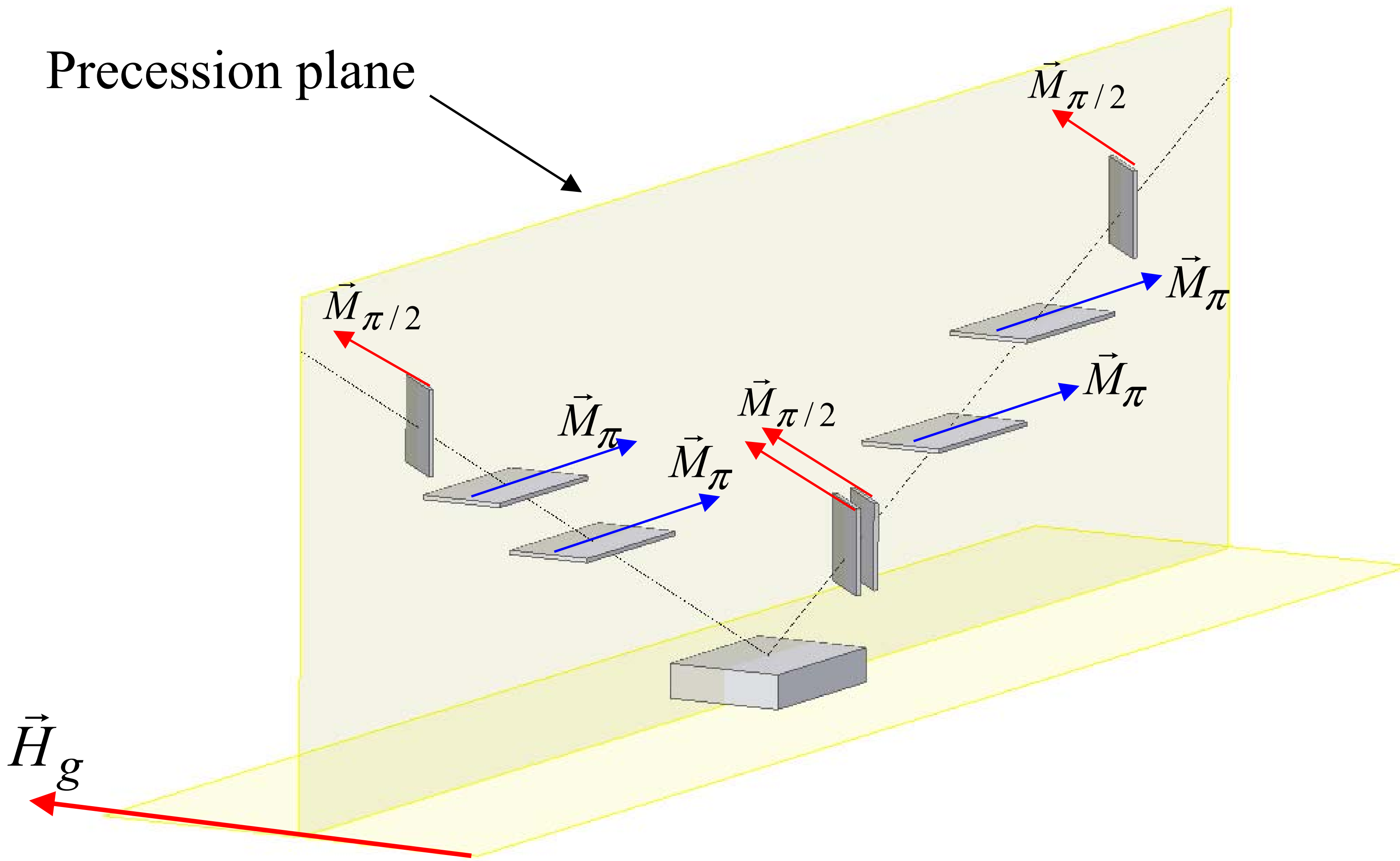
$$\phi = 0 \ldots \phi_1 \ldots -\phi_1 .. (\phi_2 - \phi_1) \ldots$$



$$\text{Net Precession} = -\phi_1 + \phi_2 - \phi_3 + \phi_4 - \phi_5 + \phi_6$$

- Total net precession angle = $(\phi_4 + \phi_5 + \phi_6) - (\phi_1 + \phi_2 + \phi_3) + 2(\phi_2 - \phi_5)$
- The first two terms depend on neutron velocity only, last term depends on velocity *and* angle of neutron trajectory
  - Requires suitably oriented planar π rotators (flippers)
- Can be set up to encode two, mutually perpendicular, trajectory angles

Using Sign-Reversal for Reflectometry



The NSE Technique May Provide a Way to Enhance Signal Intensity & Resolution for *Elastic* Scattering

- The method can be applied to achieve good resolution without the need for tight monochromatization and collimation
  - Extend size range for SANS
  - ~100x gain in measurement speed for SANS at same resolution & accuracy
  - Separate specular and diffuse (or incoherent) scattering in reflectometry
  - Measure in-plane ordering in thin films (Felcher)

- The method can be combined with real-space focusing techniques such as focusing supermirrors or lenses

- Thin permalloy films work as neutron spin rotation devices and allow implementation of “sign reversal” method
  - Only demonstrated for constant wavelength spectrometers but can probably be achieved for white beams